AFRL-RH-WP-TR-2015-0030

Performance Assessment of Active Hearing Protection Devices

Hilary L. Gallagher
Richard L. McKinley
Warfighter Interface Division
Battlespace Acoustics Branch
Wright-Patterson AFB, OH

Melissa A. Theis
Oak Ridge Institute for Science and Education
Oak Ridge, TN

Billy J. Swayne
Eric R. Thompson
Ball Aerospace & Technologies Corp.
Dayton, OH

May 2015

Interim Report

Distribution A: Approved for public release; distribution unlimited.

STINFO COPY

AIR FORCE RESEARCH LABORATORY
711 HUMAN PERFORMANCE WING
HUMAN EFFECTIVENESS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNTED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TR-2015-0030 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//signed//
Hilary L. Gallagher
Work Unit Manager
Battlespace Acoustics Branch

//signed//
Robert C. McKinley
Chief, Battlespace Acoustics Branch
Warfighter Interface Division

//signed//
William E. Russell, Chief
Warfighter Interface Division
Human Effectiveness Directorate
711 Human Performance Wing

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
08-05-2015	Interim	Feb 2014 – August 2014

4. TITLE AND SUBTITLE

Performance Assessment of Active Hearing Protection Devices

5a. CONTRACT NUMBER FA8650-14-D-6501

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 62202F

6. AUTHOR(S)

Hilary L. Gallagher
Richard L. McKinley
Melissa A. Theis *
Billy J. Swayne and Eric R. Thompson**

5d. PROJECT NUMBER 5129

5e. TASK NUMBER 512916

5f. WORK UNIT NUMBER H0K8/512916EX

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
711 HPW/RHCB
2610 Seventh St, Bldg 441
WPAFB, OH 45433

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-RH-WP-TR-2015-0030

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Materiel Command
Air Force Research Laboratory
711 Human Performance Wing
Human Effectiveness Directorate
Warfighter Interface Division
Battlespace Acoustics Branch
Wright-Patterson AFB OH 45433

*Oak Ridge Institute for Science and Education
Oak Ridge, TN 37831

**Ball Aerospace & Technologies
Dayton, OH

10. SPONSOR/MONITOR'S ACRONYM(S)

711 HPW/RHCB

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-RH-WP-TR-2015-0030

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

88 ABW/PA Cleared 07/20/2015; 88ABW-2015-3675.

14. ABSTRACT

Active electronic hearing protection devices are designed for those who want to maintain natural hearing while protecting their ears from impulse and continuous loud noises like gunfire, explosions, vehicles, and machinery. There are potential advantages for this technology in military applications, provided an accurate and complete assessment of the performance has been obtained. Five active hearing protection devices were assessed for: continuous noise attenuation, impulsive peak insertion loss, sound localization, auditory detection, and subjective comfort. The expected ambient noise environment and the task to be performed should be considered when selecting a hearing protection device.

15. SUBJECT TERMS Active hearing protection, electronic hearing protection, noise attenuation, localization, auditory detection, blast, impulse, real ear attenuation threshold (REAT), insertion loss

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Hilary Gallagher
Unclassified	Unclassified	Unclassified	SAR	31	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

THIS PAGE IS INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Understanding the noise attenuation performance of a hearing protection device is important in order to protect the user from excessive noise exposure. Active electronic hearing protection devices were designed to allow for enhanced communication and situational awareness, while at the same time protecting the auditory system from both impulsive and continuous noise. It is critical to evaluate any hearing protection device to gain an accurate and complete performance assessment. The objective of this study was to assess five active hearing protection devices for: continuous noise attenuation, impulsive peak insertion loss, sound localization, auditory detection measured using an aurally guided visual search task, and subjective comfort. The expected ambient noise environment and the task to be performed should be considered when selecting a device. The device must provide adequate hearing protection performance while maintaining or improving the performance of auditory localization and the desired level of situational awareness for the mission.

1.0 INTRODUCTION

Military ground operations take place in complex environments that necessitate creating a balance between operational effectiveness and personnel safety. The goal of effectively protecting the hearing of personnel has been complicated by the need for Marines to maintain access to acoustic cues in the ambient environment (Figure 1). Firing a small number of rounds from a weapon can cause temporary hearing loss therefore producing the undesired result of impairing the ability to monitor the environment. Repeated unprotected exposures to small arms fire that may generate these temporary changes can eventually result in permanent hearing loss. Noise exposures from larger weapons and blast events can instantly cause permanent hearing loss if no protection is worn.

Figure 1. Marine on patrol

Military personnel often work in a wide range of unpredictable noise environments. The range and uncertainty for the noise environment and mission result in the need for flexible or adaptive hearing protection to ensure mission success and survival while mitigating the risk of permanent hearing loss. Wearing a hearing protection device may degrade the user's ability to localize and detect low-level sounds, which can both be critical to situation awareness. Understanding the effects of hearing protectors on localization, as well as hearing thresholds provided information for an objective data based selection of hearing protection devices for the warfighter. The weighting of the various performance parameters could be modified relative to specific missions. Accurate measures of the performance of hearing protection/communication devices for a wide range of parameters were necessary to demonstrate sufficient mission capabilities. The assessment parameters included: continuous noise attenuation, impulsive peak insertion loss, sound localization and detection, and subjective comfort.

2.0 BACKGROUND

Development and military use of level-dependent tactical hearing protection required the development and use of new performance metrics and measurement methods[1]. These systems actively provided some level of ambient listening capability in an attempt to restore the localization cues disrupted by traditional passive earplugs and earmuffs[2,3]. Two metrics and measurement methods were developed to measure and quantify these effects. The first was a measure of localization error. This metric quantified the average error in degrees between the target location and the listener's response. A second metric was a measure of combined localization and detection. For this report, combined localization and detection was analogous to a field target acquisition task where the sound levels of the target were various low sound levels from 8 dB to 60 dB. When a user would heard the sound source, they would localize that sound source cued by a 3-D audio (spatial auditory) cue. Once the source was located, the listener visually identified the target and responded. The target acquisition time was a salient measure of the quality of the localization cue[4,5,6,7,8]. The methodology used was an aurally guided visual search task with varied sound presentation levels.

In addition to the above mentioned metrics, the Air Force Research Laboratory (AFRL) conducted a series of measures to describe the performance of hearing protection devices. The measures included passive continuous noise attenuation, impulsive noise insertion loss, input/output gain function (for active devices), localization error with short duration (250 ms) and long duration (>1 sec) stimuli, reaction time from an aurally guided visual search task with detection, and subjective comfort.

3.0 METHODS

The objective of this study was to assess five active hearing protection devices for: continuous noise attenuation, impulsive peak insertion loss, sound localization, auditory detection, and subjective comfort. The general approach was to use ANSI standard measurement procedures for continuous noise attenuation and impulsive peak insertion loss and to use AFRL defined procedures for localization error and combined detection and localization. Performance results of these devices can and should be used to determine which protectors will be made available to the warfighters and the results may also lead to design criteria for the next generation of hearing protection devices.

The overall methods are described in the following sections. The first section describes the hearing protectors that were used in the study. The following sections describe each measurement method including a description of the subjects, the facilities, and the details of the specific measurement methods.

3.1 Active Hearing Protectors

Five active hearing protectors were selected for this study: EAR Custom, EAR Mini Canal, Etymotic HD15, Open Ear Quick Fit, and Walker HD Power Elite (Figure 2). Devices measured for this study were classified as either in-the-ear (ITE) or behind-the-ear (BTE) units. The ITE units were the EAR Custom, EAR Mini Canal, and Etymotic HD15. The ear tip was fit inside the canal and the electronics casing rested in the outer ear. The BTE units were the Open EAR Quick Fit and the Walker HD Power Elite. For BTE units, the electronics, controls, microphone, and battery compartment were housed in a case that rests behind the pinna. The case was connected to the ear tip via a plastic tube and small plastic angled fitting. Both types could be worn monaurally or binaurally. For this study, all measurements were conducted with the devices worn binaurally.

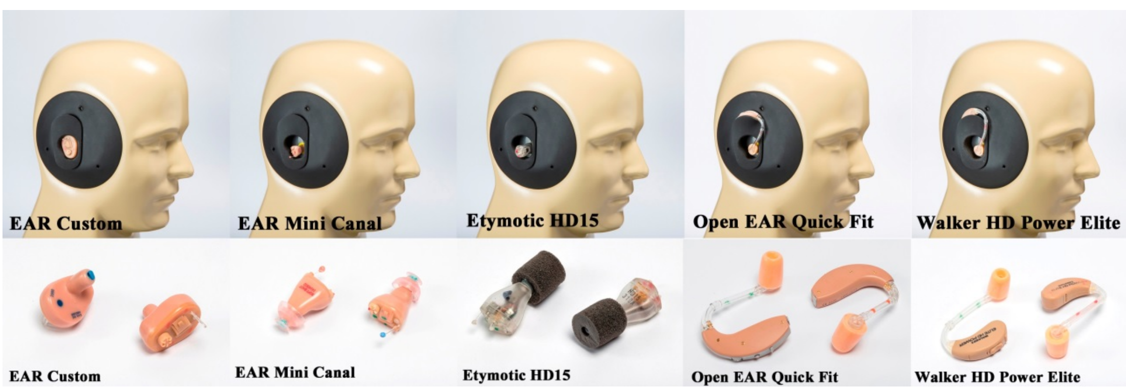

Figure 2. Active hearing protectors

3.1.1 In-the-Ear (ITE) Devices

The EAR Custom devices by EAR, Inc. were custom molded, full concha units designed and manufactured for a specific end user. A full concha earplug is one in which the device completely fills the entire portion of the outer ear referred to as the concha bowl. The EAR Customs were equipped with a single knob for volume control. The EAR Mini Canal by EAR, Inc. were ITE units designed to be worn with reusable silicone single-flange tips, available in small, medium, and large. This unit was equipped with a knob for volume control and a memory button to toggle though three different listening profiles. The first setting was for standard listening (amplifies quiet sounds), the second was for reducing background noise, and the third was for muting the device. Measurements were conducted under the first memory setting. Etymotic Research's

HD15 were ITE units designed to be worn with disposable foam ear tips, available in small and large. The HD15 were equipped with a two position switch that allowed the user to toggle between a setting that provides 15dB of attenuation when steady-state noise exceeds roughly 80 dB, and a setting that amplifies soft and conversational sounds. Measurements were conducted in the former setting.

3.1.2 Behind-the Ear (BTE) Devices

The Open EAR Quick Fit by EAR, Inc. and the Walker HD Power Elite by Walker's Game Ear, were both BTE units designed to be worn with disposable foam ear tips. The Open EAR Quick Fit units were equipped with a dial to adjust the volume and a memory setting button. The memory settings were identical to the EAR Mini Canal with the addition of a setting used for steady-state noise environments. Measurements were conducted under the standard listening setting. The Walker HD Power Elite were equipped with a toggle switch that controls both the volume and memory settings. The four memory settings for this unit were similar to that of the Open EAR Quick Fit except, instead of a mute setting, this device featured a power boost "nature" setting that amplifies high frequency sounds from far away. Once again, the standard listening setting was used for this study. The Open EAR Quick Fit units were measured with Comply™ Isolation foam insert tips, available in slim, short, standard, and large. The Walker HD Power Elite were measured with foam tips manufactured by Walker's Game Ear, available in one size only.

3.1.3 Device Gain Setting

The devices selected for this study were all equipped with a hear-thru setting designed to amplify soft sounds and conversational speech while allowing loud sounds to pass though without amplification. To normalize the hear-thru setting across devices, a unity gain measurement was captured in the Audio Localization Facility (ALF) at Wright Patterson Air Force Base (WPAFB). The unity gain refers to the volume setting at which the input/output gain curve of the device best matches the input/output gain curve of the Knowles Electronic Manikin for Acoustic Research (KEMAR). Matching the gain structures for all the devices created a baseline volume setting and provided the most accurate comparison of how each device performs in relation to other devices.

KEMAR was equipped with two G.R.A.S Type 26-AC preamps and 40AO prepolarized pressure microphones positioned inside the head, with the microphone diaphragms aligned to each ear canal. KEMAR's gain structure was obtained by measuring a series of sounds in ALF with the manikin's ears unoccluded. The unity gain of each device was determined by activating the hear-thru setting, equipping KEMAR with the device, and collecting the same series of sounds. Starting from either the maximum or minimum volume, the level of each device was adjusted until the gain structure of the device matched that of KEMAR. In some instances the gain structures didn't perfectly align at any of the available volume settings. In those cases, the level that most closely matched KEMAR's gain structure at 65 dB was selected. 65 dB is the stimulus presentation level for the localization portion of this study. The input/output gain curve for each device is displayed below (Figure 3) and the unity gain settings are provided in Table 1. All memory settings, if applicable, were set to the default setting that was selected when the unit was powered on. All default setting for these devices were denoted as “standard listening” in the respective devices’ operation manual.

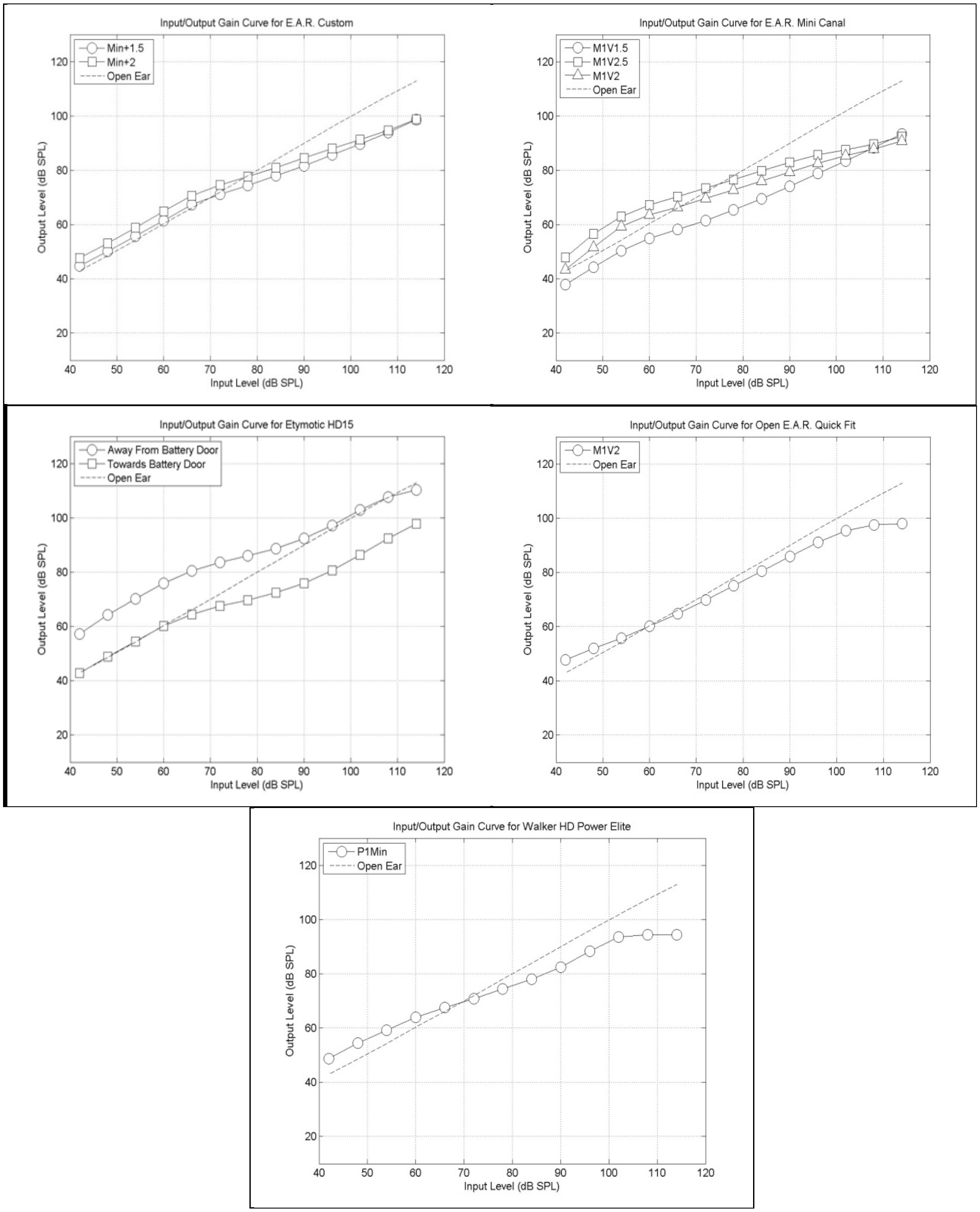

Figure 3. Input/Output gain curves for active devices in hear-thru mode. Dotted line is KEMAR response open ear. Line with circles is KEMAR response with device.

Table 1. Unity gain and memory settings for impulsive peak insertion loss, sound localization, and auditory detection measurements

Hearing Protector	Unity Gain Setting	Memory Setting
EAR Custom	1.5*	N/A
EAR Mini Canal	2*	1
Etymotic ER 125 HD15	Switch Towards Battery Door	N/A
Open EAR Quick Fit	2	1
Walker HD Power Elite	Minimum	1
** The hash marks are counted as 1.*		

3.2 Continuous Noise Attenuation

The first part of the assessment involved measuring the continuous noise attenuation performance of the five selected earplugs in the "passive" (electronics off) condition using human subjects. All human subjects were compensated volunteers. There were ten male and ten female subjects, ranging in age from 18 to 34 years. All subjects were required to have a computer administered screening audiogram via Hughson-Westlake method, with behavioral hearing thresholds inside the normal hearing range, which was 25 dB hearing level (HL) or better from 125 Hz to 8000 Hz. Ear canal sizes were verified to be sufficient to accommodate the earplugs measured in this study.

The facility used for this portion of the study was specifically built for the measurement of the sound attenuation properties of passive hearing protection devices. The chamber (Figure 4), its instrumentation, and measurement procedures were in accordance with ANSI S12.6-2008[9]. This standard describes the measurement of the occluded and unoccluded hearing threshold of human subjects using a von Békésy tracking task. The thresholds were measured two times for the unoccluded ear condition and two times for the occluded condition (with devices in place). The real-ear attenuation at threshold for each subject was computed at each octave-band frequency, 125 to 8000 Hz, by averaging the two trials (the difference between unoccluded and occluded ear hearing thresholds). The mean and standard deviation were then calculated across all the subjects.

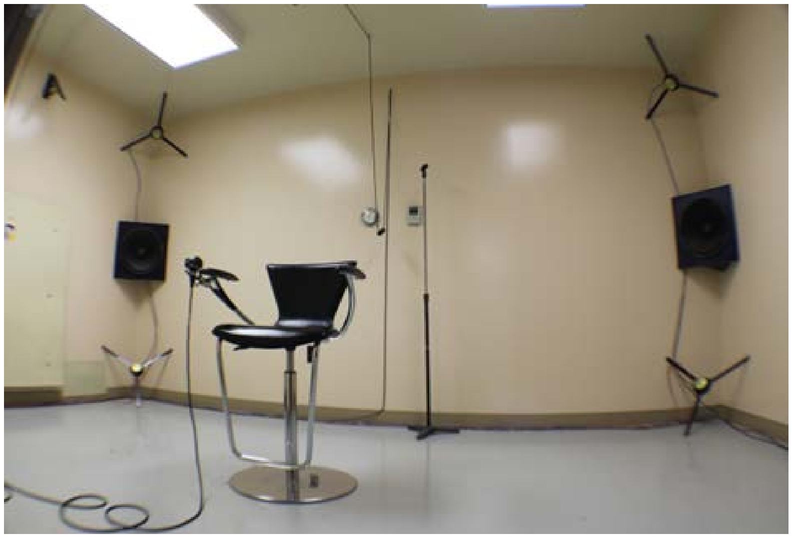

Figure 4. Facility used for measurement of continuous noise attenuation

3.3 Impulse Noise Attenuation

The objective of this portion of the assessment was to evaluate the impulsive noise attenuation performance of the five active hearing protectors when exposed to acoustic blast (impulse noise) with high peak pressure levels. Impulsive peak insertion loss (IPIL) data were calculated at multiple peak noise levels ranging from 170 dB to 195 dB sound pressure level (SPL). Devices were measured in both passive (electronics off) and active or hear-thru (electronics on) modes. The unity gain settings (Table 1) were used for all measurements conducted in the hear-thru mode.

IPIL (i.e., reduction in peak pressure of the impulse noise) measurements were conducted to determine the effect an acoustic blast may have on the auditory system of the user. Four acoustic test fixtures (ATFs) were used simultaneously in these measurements to allow for the evaluation of different hearing protectors at one time. The ATFs were ISL-1 type heads equipped with ¼" microphones in the ear canals. Each ATF was fit with a hearing protector and was exposed to acoustic blasts. IPIL data was calculated at 170, 185, and 195 dB SPL peak levels. The measurements were collected in accordance with ANSI S12.42-2010[10] Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise using Microphone-In-Real-Ear or Acoustic Test Fixture Procedures. ANSI S12.42 requires a measurement at 130 dB SPL and 150 dB SPL; however, measurements were conducted at 185 and 195 dB SPL, to reflect a more typical of a blast that a user may be exposed to in a military setting.

The measurements were conducted on the test range of the French-German Research Institute of St. Louis (ISL) situated in Baldersheim, France. The test area being used for the measurements was equipped in a way to allow the detonation of an equivalent of 300g of C4™ explosive. Using this mass of explosive it was possible to initiate a shockwave with a peak pressure level of up to 195 dB SPL and an A-duration of about 1.5 ms. The A-duration duration of the positive pressure wave is defined as the time between the beginning of an impulse (ambient) and the first zero crossing of the sound pressure level, Figure 5.

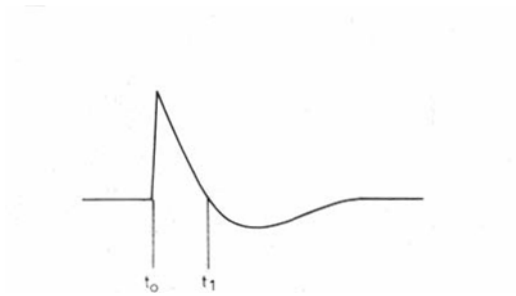

Figure 5. A-duration of an impulse noise

A ¼” microphone or slender probe (tapered pencil gauge) was used to measure the free-field pressure wave according to the International Test Operations Procedures (ITOP) 4-2-822, Electronic Measurement of Airblast Overpressure and Impulse Noise.[11] Figure 6 shows the placement of the ATFs as well as the free-field pressure transducer during the blast measurements. For each blast, the sound pressure level at 9 transducers was recorded. This included 8 signals from the ATFs, each equipped with two microphones and pre-amplifiers (one for each “ear drum”) and 1 signal from the free-field pressure transducer (slender probe).

Figure 6. Placement of ATFs and free-field pressure transducer

Pressure measurements were recorded using 16-bit digital recorders at a sampling rate of 100 kHz. In order to visualize the movements of the hearing protectors, at least 1 high-speed video (50,000 frames per second) was recorded of the ATFs right ear at 195 dB SPL for each earplug.

Initially, an open ear measurement (no hearing protector) was conducted to calculate the free-field to ear canal transfer function using a 150 dB SPL nominal peak noise level with an A-duration of 2 ms, Figure 7. The Transfer Function of the Open Ear (TFOE) was used to determine the IPIL for each fit of the hearing protector. 05/

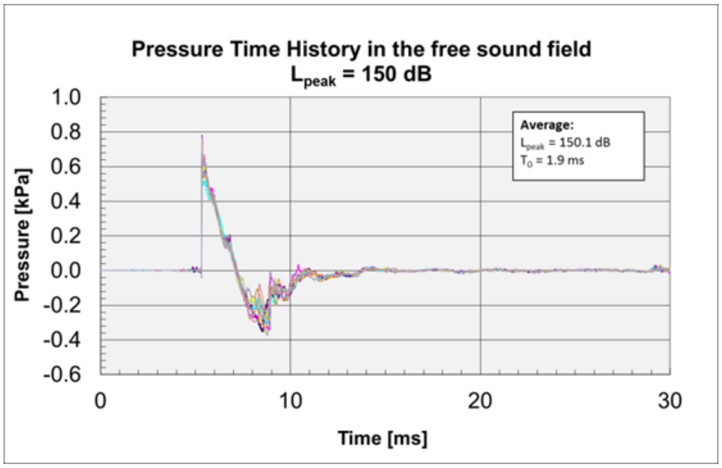

Figure 7. Pressure-time history of the impulses generated for the determination of the TFOE

For the calculation of the Insertion Loss (IL), the TFOE was calculated for all 1/3 octave-bands centered between 25 and 16 kHz. The TFOEs were used to determine the IPIL; the complex transfer function with a resolution of 6.1 Hz has been calculated. Mean TFOE for left and right ears separately are shown in Figure 8.

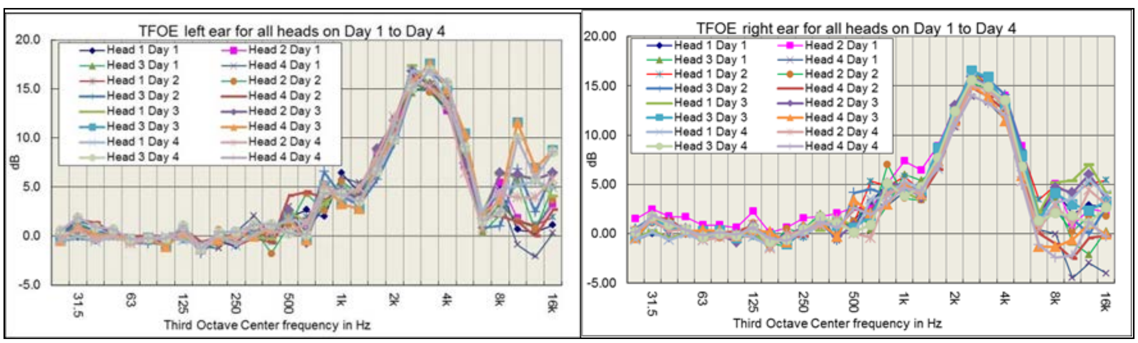

Figure 8. Mean TFOE for each head each day, left and right ear

After the determination of the TFOE, the measurements were conducted with the different hearing protectors in place. Each hearing protector was measured five times at each peak noise level; each time, the hearing protector was removed and refitted or replaced by a hearing protector of the same type.

The impulse (blast) waves were generated by explosives. Figure 9 shows a schematic of the set-up. The type and the mass of explosive as well as the distance between the explosive and the ATF determined the peak noise level and the A-duration of the generated signal, Table 2. Figure 10 shows an example of the pressure time history and sound spectrum for a 170 dB SPL noise level.

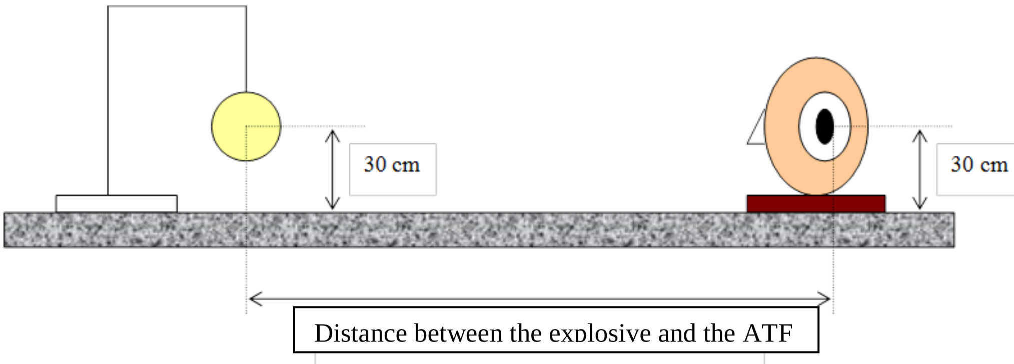

Figure 9. Schematic of the set-up of the explosive charge for the creation of a shock wave

Table 2. Type and mass of explosive and distance between ATF and explosive for different peak pressure levels and A-durations

Peak Noise Level (dB SPL)	Explosive Type	Mass (g)	Distance from ATF (m)	Measured Average A-Duration (ms)	Measured Average Peak Noise Level (dB SPL)
170	Primer (RDX 95/5)	35	6.5	2.3	170.8 (0.991 psi)
185	C4	130	3.4	2.2	184.6 (4.85 psi)
195	C4	300	2.2	1.7	195.9 (17.82 psi)

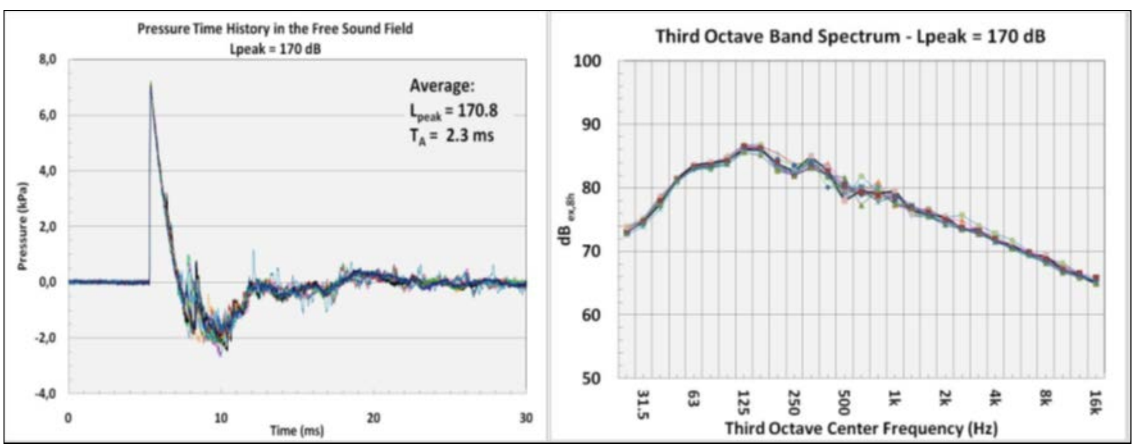

Figure 10. Pressure time history and 1/3 octave band spectrum for the 170 dB SPL noise level

3.4 Auditory Localization Error

Localization response measurements were collected for subjects wearing the five active hearing protectors in hear-thru mode. Eight paid volunteer subjects, four male and four female subjects ranging from 18 to 32 years of age, participated in the measurements. All subjects had bilateral hearing threshold levels less than or equal to 15 dB from 125 to 8000 Hz.

All measurements were collected in the Auditory Localization Facility (ALF) (Figure 11) at WPAFB. The aluminum-frame geodesic sphere is 14 feet in diameter with 4.5 inch loudspeakers, each of which was equipped with four light-emitting diodes (LEDs) located at each of the 277 vertices on its inside surface. The ALF apparatus is housed within an anechoic chamber. The subject stood on a platform in the center of this sphere. The location of the platform has the potential to distort the signals from the speakers located directly below the subject, therefore only 237 loudspeakers, evenly distributed, above -45° elevation, were used in this study. The distance between speakers ranged roughly between 8° and 15°.

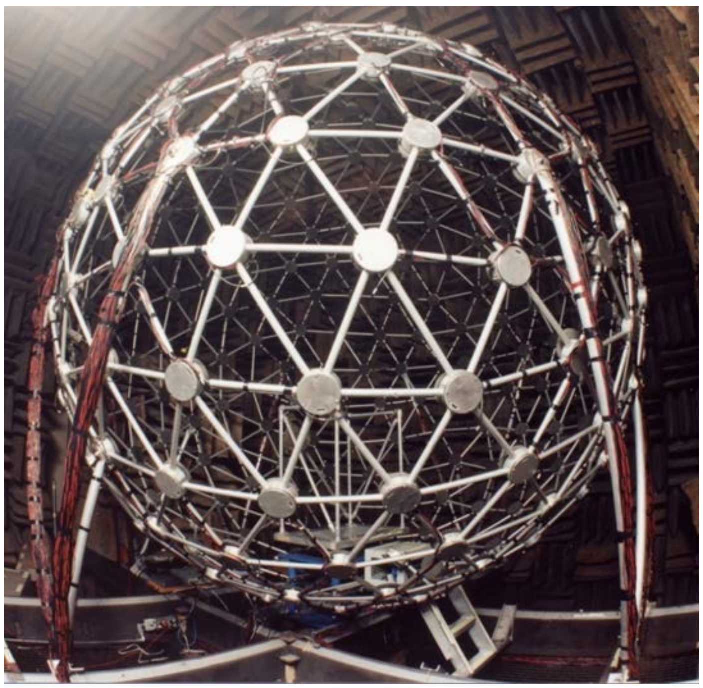

Figure 11. Auditory Localization Facility (ALF) at WPAFB

Subjects registered their responses with an Intersense IS-900 tracking system (Figure 12). The IS-900 used inertial-ultrasonic hybrid tracking technology to provide precise position and orientation information. The tracking system included a head tracker coupled with a response wand. The head tracker was mounted on the subjects' head to provide tracking data on the X, Y, and Z coordinate location of the head, as well as the yaw, pitch and roll during the duration of each trial. The head tracker also assisted the subject in aligning his/her head to the 0° azimuth, 0° elevation speaker location to begin each trial. The response wand was equipped with a joystick and five buttons which could be programmed for various purposes depending on the task. For this study, the subjects were required to press a single button while pointing the wand at their desired response location.

Figure 12. Intersense IS-900 tracking system

The stimuli were presented to the subjects in two different conditions. In one condition, the stimulus was a 250-ms burst of broadband (200 Hz - 16 kHz) pink noise. This duration was chosen in order to reduce the possibility that a subject would initiate a head movement during the stimulus presentation. Such a movement would provide dynamic localization cues, which would result in improved performance. In addition many real world sounds encountered by the user are likely to be short duration (e.g. weapons fire, explosions). In another condition, a broadband (200 Hz - 16 kHz) pink noise was presented continuously until a localization response was made. This allowed subjects to make use of dynamic localization cues and move their heads during stimulus presentation to orient to the sound.

The order in which each hearing protection device was measured was randomized across subjects in order to eliminate any order effects. The subjects also completed an "Open" measurement (without hearing protection) as a baseline. The experiment was coded and executed using the MATLAB programming language by Mathworks™. For each measurement the subject fit him/herself with the appropriate hearing protector according to the directions provided by the manufacturer. The fit was verified by the experimenter. The experimenter then directed the subject from the control room, where the fitting took place, into ALF. Once inside the sphere, the standing subject was raised or lowered by adjusting the height of the platform to ensure the subject's head was in the center of the sphere.

To start each trial the subject aligned his/her head to a loudspeaker located directly in front of them (0° azimuth, 0° elevation) and pressed a button on the response wand. A stimulus was presented randomly from one of the 237 speakers in the sphere. The stimulus was either a 250 ms burst of pink noise or a presentation of continuous pink noise. The subject would then locate and select the target speaker by pointing at it with the wand and clicking the response button to enter his/her selection. The LEDs on the speakers were tracked to the wand's movement so the subject could verify the location of his/her response. After a response was recorded, the LEDs of the target speaker were activated to give the subject feedback on his/her performance.

Each of the eight subjects completed 320 trials in the burst noise condition and 64 trials under the continuous noise condition for each of the five active hearing protectors and one control condition in which no hearing protection was worn. The ratio of burst stimuli continuous stimuli was weighted 5 to 1. The burst stimuli modeled sounds in the environment which were short (250 ms) in duration and only occurred once, such as a rifle bolt closing, while the continuous stimuli modeled continuous noise sources such as vehicles. Both burst and continuous stimuli were presented in a single block of trials. All stimuli were presented at 65 dB.

3.5 Aurally Guided Visual Search with Detection

Reaction time (time to auditorily detect, locate, and visually identify the source location) measurements were collected for subjects wearing the five active hearing protectors in hear-thru mode. Eight paid volunteer subjects participated in the measurements; four male and four female subjects ranging from 18 to 32 years of age. All subjects had bilateral hearing threshold levels less than or equal to 15 dB from 125 to 8000 Hz.

All measurements were collected in ALF at WPAFB. The facility design and setup, as well as the subject fitting procedure and setup procedure once inside facility, are identical to those described in the "Sound Localization" section above.

As previously indicated, a cluster of four LEDs was mounted at the center of each speaker in ALF. Subjects were tasked to complete an aurally guided visual search task where they identified a visual target in the presence of 50 visual distracters at randomly selected positions around the sphere. For this task, the target stimulus was a cluster of LEDs in which either two or four LEDs were illuminated. The distracter stimuli were clusters of LEDs with either one or three illuminated LEDs. In addition, a 250 ms burst of broadband (200 Hz - 16 kHz) pink noise was played from the speaker at the target location at a predetermined sound level. The time required for the subject to find and identify the target was measured as a function of the noise-burst SPL with each hearing protector, with open ear as a reference.

To start each trial the subject aligned his/her head with a designated loudspeaker located directly in front of them (defined as 0° azimuth, 0° elevation) and pressed the trigger button on the underside of the response wand. At this point, 50 distracter stimuli were illuminated along with the one target stimulus. The subjects' task was to quickly locate the target stimulus and identify whether two or four LEDs were illuminated at the target location by pressing a response button on the top of the ALF response wand. After the subject recorded his/her response, he/she would realign to the front speaker to begin the next trial.

The subjects were randomly assigned hearing protectors in order to eliminate any order effects. The subjects also completed an "Open" measurement (without hearing protection) as a baseline. Each of the eight subjects completed 360 trials per hearing protector, with 60 trials at each of the six different sound levels. In addition, each subject completed 60 trails in an unoccluded visual only condition. This condition was added to create a worst case scenario situation where the subject was given no auditory cue and forced to visually search for the target. Detection performance with the hearing protectors was measured with a target stimulus SPL ranging from 19 dB to 80 dB. Performance during an aurally guided visual search was also measured with open ear as a reference with 60 trials at each of the following SPLs: 19 dB, 25 dB, 40 dB, 50 dB, and 70 dB. Levels were selected for each hearing protector that spanned a range from quiet (inaudible) to clearly audible (not to exceed 85 dB SPL at the eardrum). Note: A digital to analog converter failed at the beginning of the aurally guided visual search measurement and was replaced. Post-test calibration revealed that the actual sound levels were 1.2 dB lower with the new unit than the values reported for this section of the report. The actual levels during this measurement were 17.8 dB, 23.8 dB, 38.8 dB, 48.8 dB, 68.8 dB, and 78.8 dB.

3.6 Subjective Comfort Questionnaire

Subjective comfort questionnaires can be very useful tools to identify if devices will be readily accepted by the end user. Fantastic attenuation and performance alone is useless if the device is so uncomfortable that few individuals will tolerate wearing it. The subjects filled out a subjective questionnaire immediately after testing with each device. The following questions were used to rank the earplug comfort for these devices:

For the questions below, please use this rating scale:
1 - Very comfortable
2 - Somewhat comfortable
3 - Neither comfortable or uncomfortable
4 - Somewhat uncomfortable
5 - Very uncomfortable

Describe the level of discomfort during insertion	1	2	3	4	5
Describe the level of discomfort during removal	1	2	3	4	5
Describe the level of discomfort after removal	1	2	3	4	5
After earplug insertion, describe the level of discomfort over time	1	2	3	4	5

4.0 RESULTS

4.1 Continuous Noise Attenuation Results

Passive noise attenuation measurements, for protection in a continuous noise environment, were collected in accordance with ANSI S12.6 for all five devices in the "off" condition. Mean and standard deviation noise attenuation data were calculated across subjects at each frequency (Table 3). A single Noise Reduction Rating (NRR) was also calculated for mean minus 1 and mean minus 2 standard deviations, Table 3. Figure 13 displays a graphical representation of the attenuation at each frequency tested (mean minus 2 standard deviations).

Table 3. Passive mean and standard deviation noise attenuation for all devices, electronics off and the calculated NRR (mean minus 1 and 2 standard deviations (SD))

Hearing Protector		Frequency (Hz)							NRR	
		125	250	500	1000	2000	4000	8000	Mean -1SD	Mean -2SD
EAR Custom	Mean	15	15	16	21	28	34	33	13	6
	SD	8	8	8	7	5	5	8		
EAR Mini Canal	Mean	26	24	26	29	31	32	35	23	18
	SD	6	5	6	5	5	5	7		
Etymotic ER125 HD15	Mean	28	29	31	36	34	37	43	26	19
	SD	9	8	8	7	4	5	6		
Open EAR Quick Fit	Mean	27	28	30	32	33	40	44	27	22
	SD	5	6	6	5	3	2	3		
Walker HD Power Elite	Mean	24	23	25	30	32	37	40	21	14
	SD	9	8	8	7	5	4	7		

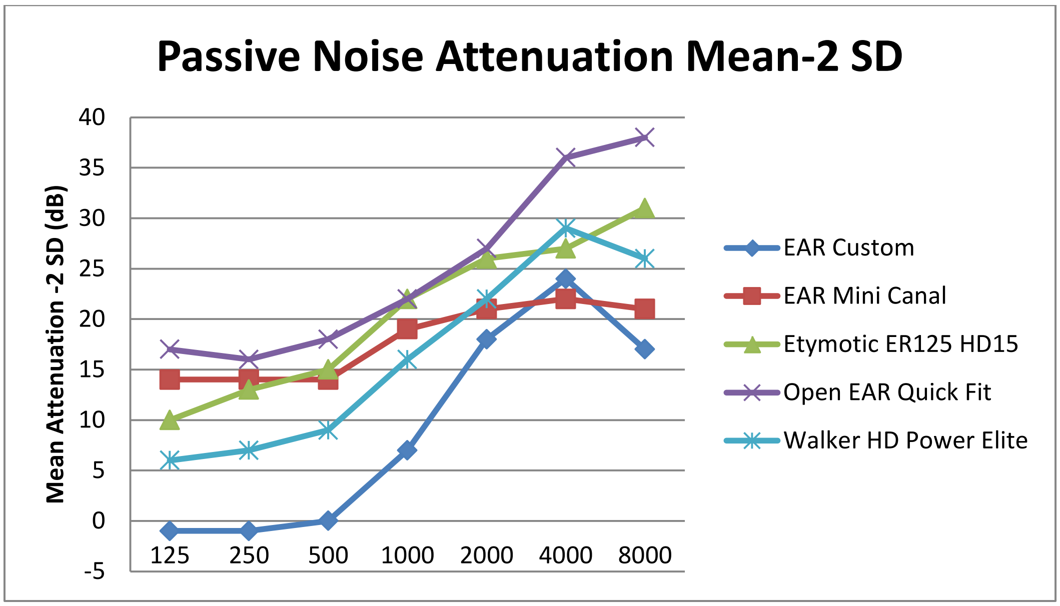

Figure 13. Passive mean minus 2 standard deviation noise attenuation for all devices, electronics off

Passive noise attenuation data were also analyzed using the methods described in ANSI S12.68. This ANSI standard details the methods for estimating the effective A-weighted SPL when hearing protectors are worn. The Noise Level Reduction Statistics for use with A-Weighting (NRS_A) and the Noise Level Reduction Statistics, Graphical (NRS_G) were calculated for all the earplugs (Tables 4 and 5, respectively).

NRS_A can be used by subtracting the value from the A-weighted noise level to estimate the level of sound under the hearing protector. This method offers several advantages over the well-known NRR. The NRR is designed to be subtracted from the C-weighted noise exposure, with an easily forgotten 7-dB adjustment that must be applied prior to subtracting it from A-weighted exposure values. C-weighted exposure values are often not known, and therefore the rating for subtraction from A-weighted exposures with the NRS_A eliminates these problems with the NRR. Another advantage of the NRS_A is that it calculates two levels of protection to indicate the range of performance that was achieved; this range reflects both the variation across the subjects in the test panel providing insight into how hard/easy the device may be to fit, as well as variation in noise level reduction with the noise spectrum in which the device is used[12]. The majority of users (80%) will achieve the performance specified by the lower value in the range, with only the most motivated proficient users (20%) able to achieve or exceed the higher value. A narrow range provides knowledge that the device is more stable and provides more predictable protection. For this data set, the device with the smallest range was the Open EAR Quick Fit with a range of 6 dB, and the device with the largest range of 12 dB was the EAR Custom.

Table 4. NRS_A results for all devices (electronics off)

Hearing Protector	80%	20%
EAR Custom	15.2	27.4
EAR Mini Canal	24.9	32.1
Etymotic ER125 HD15	28.1	38
Open EAR Quick Fit	29	35.1
Walker HD Power Elite	23.3	33.9

The NRS_G rating requires knowledge of both the C- and A-weighted noise levels, and uses this additional information about the noise spectrum to more precisely estimate the range of protection provided. For example, if the C-weighted noise is measured at 100 dB and the A-weighted noise is measured at 94 dB then the difference between the two weighting levels is 6. Therefore, the range of protection provided by the hearing protector could be found in Table 5 where B = 6. NRS_A is appropriate for unpredictable noise environments that may vary widely as is the case with many military operations. However, if one is considering a noise environment that is relatively constant (e.g., dominated by low frequencies such as an aircraft or other vehicles), then NRS_G should be used to calculate more accurate attenuation performance values.

Table 5. NRS_G results for all devices (electronics off)

Hearing Protector	Percent	$B=L_C - L_A$			
		-1	2	6	13
EAR Custom	**80%**	20.8	14.2	11.3	9
	20%	30.9	25.8	23.5	21.8
EAR Mini Canal	**80%**	26.8	24.4	22.5	20.8
	20%	33.9	31.7	30.6	30.1
Etymotic ER125 HD15	**80%**	31	27.5	24.8	21.7
	20%	39	37.7	36.6	35.7
Open EAR Quick Fit	**80%**	32.5	28.3	26.2	23.9
	20%	36.7	34.4	33.3	31.5
Walker HD Power Elite	**80%**	27.6	22.4	19.6	17.2
	20%	36	33.1	31.6	30.5

4.2 Impulse Noise Attenuation Results

Impulsive peak insertion loss measurements were collected in accordance with ANSI S12.42 for all devices (powered on and off). The insertion loss for each ear and each peak pressure level were recorded. Figure 14 displays an example graph of insertion loss for the Etymotic HD15 during a 170 dB blast event. Table 6 lists the average IPIL for each device at 170, 185, and 195 dB.

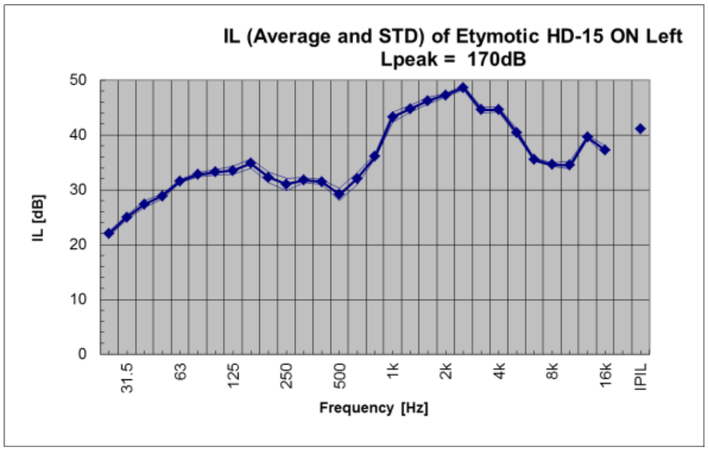

Figure 14. Example insertion loss data from Etymotic HD-15 device, left ear of ATF

Table 6. Average Impulse Peak Insertion Loss (IPIL) data from blast measurements

Hearing Protector	170 dB SPL	185 dB SPL	195 dB SPL
EAR Custom OFF *	44.5	43.4	41.9
EAR Custom ON *	44.4	44.6	44.4
EAR Mini Canal OFF	38	38.5	42.4
EAR Mini Canal ON	38.4	39.9	43.3
Etymotic ER125 HD15 OFF	39.1	40.7	44
Etymotic ER125 HD15 ON	40.4	38.2	44.9
Open EAR Quick Fit OFF	42.7	44.3	46
Open EAR Quick Fit ON	38.8	40.5	43.1
Walker HD Power Elite OFF	40.7	42.5	45.1
Walker HD Power Elite ON	41.1	42.6	45.2

*High attenuation results due to unrealistic custom fit to an ATF when compared to what is achievable with a human ear

4.3 Auditory Localization Results

Two metrics of particular interest were percentage of angular errors > 45˚, and percentage of front-back reversals. Both of these metrics were obtained from the same data set. Table 7 and Figure 15 show the percentage of mean angular errors that were greater than 45º with each hearing protector for the burst and continuous noise conditions. Angular error is the difference between the actual target location and the subject's response location as measured by the distance between the two points along the surface of the sphere. The rationale behind this measurement was its operational relevance. In general, we assume that if an operator's attention can be directed to within 45°, he/she will then be able to use other sensory information, especially vision, to acquire the target. Subject data was collected with an "open" ear configuration (no hearing protection device). In this configuration the subjects only had errors greater than 45° 1.6% of the time in the burst noise condition and 0.4% in the continuous noise condition. Localization performance is degraded when a hearing protection device is worn when compared to the localization performance when no hearing protection device is worn. The hearing protector with the lowest percentage of errors greater than 45º was the EAR Mini Canal for the burst conditions and Walker HD Power Elite for the continuous noise condition. The hearing protector with the highest percentage of errors greater than 45º was the Etymotic HD15 for both the burst and continuous conditions.

Table 7. Percentage of mean angular errors > 45˚ for burst and continuous noise conditions

Hearing Protector	Burst	Continuous
Open	1.6	0.4
EAR Custom	29.8	16.6
EAR Mini Canal	24.3	9.0
Etymotic ER125 HD15	38.4	24.4
Open EAR Quick Fit	38.1	17.3
Walker HD Power Elite	33.7	8.5

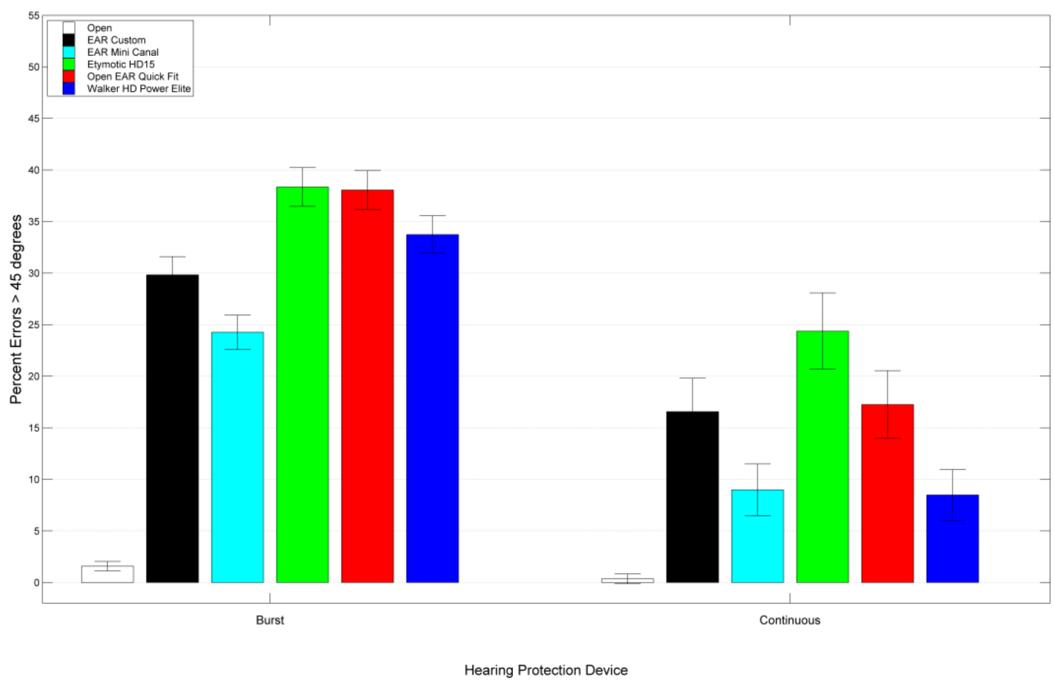

Figure 15. Percentage of mean angular errors > 45˚ for burst and continuous noise conditions

Front-back reversals occur when a subject is unable to determine whether a sound is in front of them or behind them. The percentage of front-back reversals is displayed in Table 8 and Figure 16. Again, subject data was collected with an "open" ear configuration (no hearing protection device). In this configuration the subjects only had front-back confusions 4.0% of the time in the burst noise condition and 0.9% in the continuous noise condition. For the burst conditions, the hearing protector with the lowest percentage of front-back reversals was the EAR Custom; the highest percentage was the Open EAR Quick Fit. The percentage of front-back reversals for the continuous noise conditions more closely matched the open ear data with a range of 1.6% to 5.4%.

Table 8. Percentage of front-back reversals for the burst and continuous noise conditions

Hearing Protector	Burst	Continuous
Open	4.0	0.9
EAR Custom	17.6	2.8
EAR Mini Canal	20.4	4.0
Etymotic ER125 HD15	22.4	5.4
Open EAR Quick Fit	30.1	1.6
Walker HD Power Elite	26.0	1.6

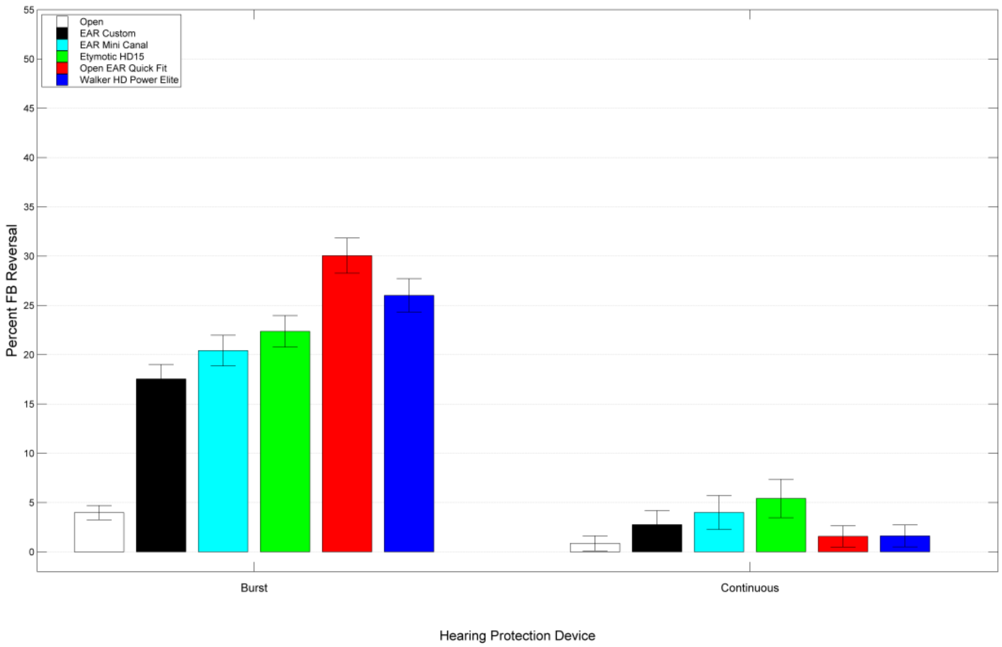

Figure 16. Percentage of front-back reversals for the burst and continuous noise condition

Distribution A: Approved for public release; distribution unlimited.
88ABW Cleared 07/20/2015; 88ABW-2015-3675.

4.4 Aurally Guided Visual Search (Auditory Detection) Results

Auditory response data were collected were both unoccluded and occluded using an aurally guided visual search task. The measured response times show a faster response time with increasing presentation level as the auditory stimuli become more audible and localizable. Subjects also completed a visual only search task with no aural guide to act as a baseline. The subjects averaged a response time of 12.2 seconds to find the target when no aural guide was provided. The average response times for all devices is presented in Table 9 and Figure 17. Overall, the shortest search times in comparison to the "Open" ear condition were achieved by donning the EAR Custom; the longest, Open EAR Quick Fit. Search times with the Etymotic HD15, Walker HD Power Elite, and EAR Mini Canal were very similar.

Table 9. Average Response Time

	Target Level (dB SPL)						
Hearing Protector	**19**	**25**	**40**	**50**	**70**	**80**	**Total**
Open	2.7	2.3	1.8	1.6	1.7		
EAR Custom	7.6	6.5	5.7	4.6	5.2	4.2	33.8
Etymotic ER125 HD15	10.5	7.1	5.3	5	6.5	4.4	38.8
Walker HD Power Elite	9.7	6.9	6	5.7	5.4	5.3	39
EAR Mini Canal	9.5	7.9	4.8	6.2	5.8	5.2	39.4
Open EAR Quick Fit	10.3	7.9	8.2	6.2	5.4	5.3	43.3

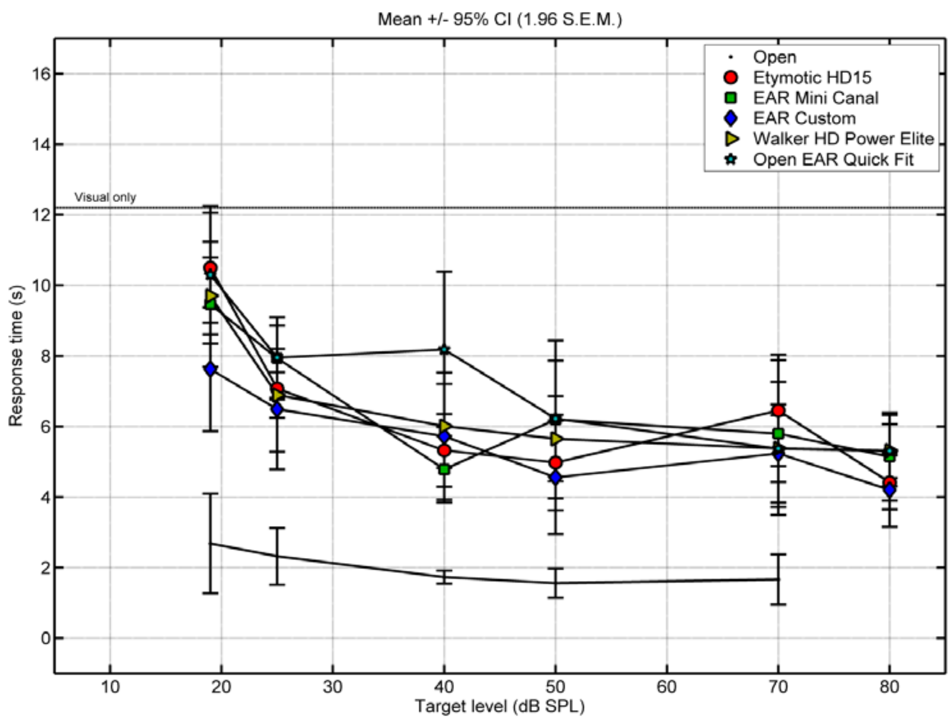

Figure 17. Average response time for an aurally guided visual search task

4.5 Subjective Comfort Questionnaire Results

Equal weighting was used for all the questions that made up the subjective questionnaire. While some of the subjects may have rated some of the devices as very uncomfortable on an individual basis, when all subjects were considered the averages indicated that none of the devices tested should be excluded solely on comfort. Table 10 shows the average subjective comfort scores of each device as well as the descriptive comfort category that was associated with the numerical value.

Table 10. Subjective Comfort Questionnaire Results

Hearing Protector	Average Comfort Value	Description of comfort
EAR Custom	1.36	Very comfortable
Etymotic ER125 HD15	1.76	Somewhat Comfortable
Walker HD Power Elite	2.10	Somewhat Comfortable
EAR Mini Canal	2.14	Somewhat Comfortable
Open EAR Quick Fit	1.64	Somewhat Comfortable

5.0 DISCUSSION

All hearing protection devices can and should be assessed in multiple ways to describe the performance of the device and the effects on the user's auditory perception. Subjective and objective measurements can be conducted to characterize a device's noise attenuation performance as well as any negative effect on situational awareness capabilities that may result. Noise attenuation in both continuous and impulse noise environments, sound localization capabilities, auditory detection capabilities, and subjective comfort were all assessed for the devices in this study.

5.1 Localization and Detection versus Attenuation

Military personnel are exposed to various noise environments depending on their mission: continuous and/or impulsive, predictable and unpredictable. Also, dependent on their mission, the performance of the hearing protection device may carry different weighting. For some missions, auditory detection and localization may be more important than sound attenuation while for other missions attenuation may be more important than localization and detection. These different weightings should be considered by those who are selecting hearing protection devices for a particular mission or group of users. It is critical to consider the environment of the end user, and evaluate the pros and cons for each assessment area independently for an informed decision. It is more advisable to pick a top performing device in the area that is most critical to the task, and to consider other variables when choosing a device. For example, there may be some missions where the expected noise levels are high, the risk of impulsive noise is low and the need for situation awareness is also low. For this mission, a device should be chosen based primarily on the continuous noise attenuation performance. However, for a different mission where ambient noise levels are expected to be low, there is some risk of impulsive noise, and good situation awareness is desired, a device should be chosen based on IPIL, localization and detection performance.

5.2 Device Fit

Other considerations beyond these performance areas exist when evaluating hearing protectors. Sizing and fit is one such consideration. With custom earpieces, fit is especially critical for attaining the maximum possible attenuation. If a custom earplug is under filled, the earpiece will fit loosely, allowing sound to enter through the gaps. If the custom earplug is overfilled, the earplug will fit too rigid and will most likely cause the user irritation and discomfort. The EAR Custom provided the least amount of continuous noise attenuation and had the widest range in attenuation values. However, the subjects' performance in the localization and auditory detection task were the greatest in comparison to the performance when the other hearing protectors were worn; in addition to being the only plug considered "very comfortable" by all participants. It is very likely that several sets of earplugs were under filled and fit loosely. Over half of the subjects noted that moving his/her head around during the measurements would break the seal on the plug and allow sound to leak in. Subjects likely used those leaks to their advantage in the localization and auditory detection measurements. It is also important to consider that impulsive noise attenuation measurements for this and all devices must be accomplished with an ATF. In the case of any custom device, the product will provide a nearly perfect acoustic seal due to the dimensions/design of the ear canal of the ATF. Therefore the impulsive attenuation data for the EAR Custom should not be considered representative of what a live human would achieve with this device. Given the known acoustic leaks that were experienced by several of the subjects, it would be reasonable to assume that less IPIL would have been achieved by live human subjects in an impulsive noise event than what was achieved with the ATF.

The EAR Mini Canal was another device that provided low attenuation and high performance in the localization/ auditory detection measurements. This was most likely attributed to the single flange ear tip. Many subjects noted that the earpieces would slowly slip out of his/her ear canals, especially in situations involving head movement, like the measurements in ALF. Silicone, by design, is slick. Also, these single flange ear tips lacked the length to properly hold the ear tip in place. Even with three sizing options, it was difficult for many subjects to maintain a proper seal with the EAR Mini Canal.

The foam tips for the Walker HD Power Elite were available in only one size, which would be comparable to a large for most foam insert tips. Seven of the twenty subjects in the continuous noise attenuation measurements were fitted for other devices with small or slim plugs. The lack of appropriate sizing options likely resulted in reduced attenuation for these devices. An adaptor was available to make Comply™ foam tips compatible with the Walker devices. If Comply™ tips were used instead of those provided by the manufacturer, continuous noise attenuation performance more similar to the Open EAR Quick Fit would be expected.

5.3 Design

Hearing protector design is another consideration. Design was a particular concern with the EAR Mini Canal. The outer portion of the device was smaller than most individual's thumbnail. The volume knob, battery door, microphone, and memory setting button were all located in this small area. The size of the volume knob made it very difficult to adjust the setting. This design made it nearly impossible to adjust while in the ear. Also, the memory setting button was located immediately next to where the user would apply pressure to insert the earpiece. This resulted in changing the memory setting almost every time the device was touched. The Etymotic HD15 was a simpler design, but bulky. The post to which the ear tip attached was very rigid, making the earplug itself rigid, which can be very uncomfortable if the device was fully inserted. If the device was not fully inserted, the electronics enclosure hung out of the ear past the concha bowl.

6.0 CONCLUSIONS

All hearing protective devices are not equally effective and their performance varies with the different measurement parameters. A full assessment should be conducted for all hearing protectors to include: continuous and impulsive noise attenuation, sound localization, auditory detection measurements and in some cases speech intelligibility before such devices are used in military applications.

Passive hearing protection devices can provide high levels of attenuation in both continuous and impulsive noise environments. However, due to the level of noise attenuation, communications and situation awareness capabilities can be negatively affected. Hearing protection devices that have active components were designed to provide the user with enhanced face to face communication abilities and amplify low level sounds to allow detection capabilities. All of the active devices that were assessed in this study caused significant impairments to localization capabilities versus the open ear, and that knowledge must be used to determine how and when such devices can be integrated successfully into a mission. Performance results of hearing protection devices can and should be used to determine the protectors will be made available to the warfighters. The results of the hearing protector performance assessments may provide insight into new technologies and/or design criteria for the next generation of hearing protection devices.

7.0 REFERENCES

1. Abel, S., Baudou, J., Bjorn, V., Buck, K., De Boodt, F., Drullman, R., Henry, P., James, S., McKinley, R.L., Sarafian, D., Van Der Veken, P., Hearing Protection - Needs, Technologies, and Performance, NATO RTO TG-147 Final Technical Report, April, 2010.
2. Brungart, D. S., Kordik, A. J., Simpson, B. D., & McKinley, R. L., Auditory localization in the horizontal plane with single and double hearing protection. *Aviation, Space, and Environmental Medicine, 74,* 937-946, 2003.
3. Bolia, R. S. & McKinley, R. L., The effects of hearing protectors on auditory localization: evidence from audio-visual target acquisition, *International Journal of Occupational Safety and Ergonomics*, Vol 6, No. 3, 309-319, 2000.

4. Bolia, R. S., D’Angelo, W. R, & McKinley, R. L., Aurally Aided Visual Search in Three-Dimensional Space, *Human Factors*, Vol 41, No. 4, 664-669, Dec 1999.
5. McKinley, R. L., & Bolia, R. S., The effects of hearing protectors on reaction times in audio-visual target acquisition. Proceedings of the 7th International Congress on Noise as a Public Health Problem, Sydney, Australia, pg 205-208, 1998.
6. McKinley, R. L., D’Angelo, W. R., Nelson, W. T., Perrott, D. R., & Bolia, R. S., Three experiments in aurally aided visual search. *Journal of the Acoustical Society of America* 102:3139, 1997.
7. McKinley, R.L., D'Angelo, William R., Haas, Michael W., Perrot, David R., Nelson, W. Todd, Hettinger, Lawrence J., Brickman, Bart J., "An Initial Study of the Effects of 3-Dimensional Auditory Cueing on Visual Target Detection," *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 119-123, October 1995.
8. Perrot, David R., Cisneros, McKinley, R. L., and D'Angelo, William R.,"Aurally Aided Detection and Identification of Visual Targets," *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 104-108, October 1995.
9. ANSI/ASA S12.6-2008, “American National Standard Methods for Measuring the Real Ear Attenuation of Hearing Protectors”.
10. ANSI S12.42-2010, “American National Standard Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise using Microphone-In-Real-Ear or Acoustic Test Fixture Procedures”.
11. International Test Operations Procedures (ITOP) 4-2-822, Electronic Measurement of Airblast Overpressure and Impulse Noise
12. Council for Accreditation in Occupational Hearing Conservation, “Redefining the NRR”, *The Newsletter of the Council for Accreditation in Occupational Hearing Conservation*, Volume 19: 2, 2007.